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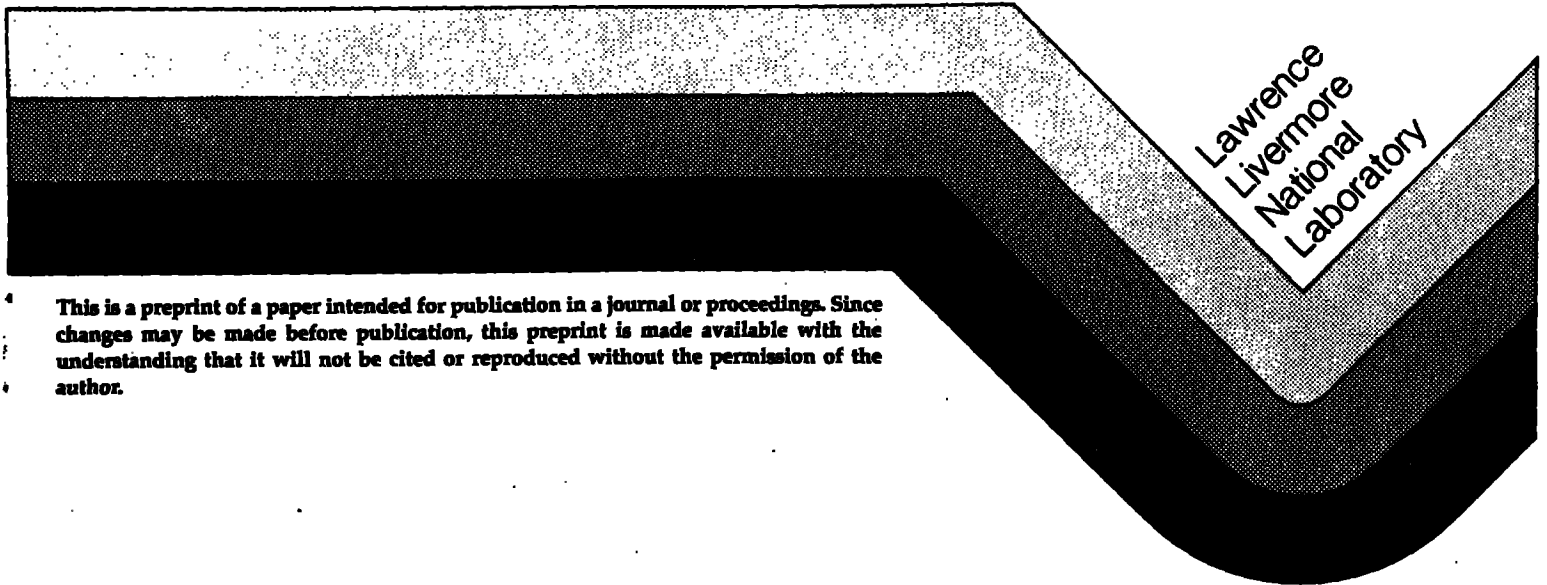
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SHEATH MATERIAL**

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IMPROVEMENTS IN THE WELDABILITY OF A SUPERCONDUCTOR SHEATH MATERIAL

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ABSTRACT

This paper investigates the effects of chemistry and heat treatment variation on the 4-K tensile properties of A-286, a candidate sheath material for force-cooled superconductors. Currently, full use of A-286 and similar superalloys is limited by the observed low yield and ultimate tensile strengths in the welded and aged condition. The low strength is shown to be associated with the formation of precipitate-free zones as a result of alloying-element segregation during weld pool solidification. It has been determined that minor modifications of the weld-metal chemistry by the addition of Ti reduce precipitate-free-zone formation, resulting in matching weld-metal and base-plate strengths at 4 K. Furthermore, nucleation of the γ' hardening phase has been found to be a strong function of temperature and composition. Modified heat-treatment schedules have been determined that are amenable to superconductor fabrication and that resulted in increased weld hardening and improved 4-K tensile properties.

INTRODUCTION

Advanced superconducting magnets will incorporate unalloyed or alloyed Nb_3Sn superconductor, surrounded by a thin-walled pressure vessel (sheath), and cooled by the forced flow of liquid helium inside the pressure vessel.^{1,2,3} This is the so-called "internally cooled coiled superconductor" (ICCS). This report details an investigation to improve the cryogenic mechanical properties of gas tungsten arc (GTA) welds of A-286, a candidate for use as the conductor pressure vessel.

The high strain sensitivity of bronze-processed Nb_3Sn superconductors requires that the conductor experience strains of less than 0.5% following the high-temperature reaction heat treatment used to

precipitate the superconducting phase.⁴ An accepted method of manufacturing ICCS conductors is to perform most fabrication steps, including wrapping and seam welding of the sheath, prior to the reaction heat treatment. Thus the conductor sheath is exposed to reaction heat treatments that are typically more than 30 hours in length and at temperatures of 700 °C or higher.

A previous investigation has shown JBK-75, an iron-base superalloy similar to A-286, to be acceptable for use as the sheath material in applications such as the Westinghouse magnet for the Oak Ridge National Laboratory Large Coil Project.⁵ However, this investigation determined that heat-treated GTA welds of JBK-75 have yield and ultimate tensile strengths that are 7 to 8% lower than similarly aged base metal.

It has been shown that the low weld strength is due to the formation of precipitate-free zones resulting from the segregation during weld pool solidification.^{6,7} Dendrite cores are consequently too lean in Ti to form the γ' hardening phase. The low weld strength has raised concern over the future use of this alloy, particularly in magnets that will encounter higher operational loads.

In the present investigation, methods of increasing the weld strength to levels approaching those of the base metal have been evaluated. This has included the use of Nb₃Sn-compatible, multistep heat treatments and weld pool chemistry control.

PROCEDURE

The starting material consisted of commercial round stock of A-286, a variant of JBK-75 that has been determined to have a similar aging response. This material was hot rolled to a thickness of 3.0 mm, sealed in stainless steel bags, and solution heat treated at 1100 °C for one hour with a final water quench. The composition of A-286 is given in Table 1.

Welding was full penetration bead on plate. All welds used a torch velocity of 2.5 mm/sec, 110-A current, and 18-V straight polarity. The heat input is estimated to be 735 J/mm. Modifications of the weld pool chemistry were made by buttering the surface of the plate with 0.4-mm-diameter, high-purity Ti wires. Two weld compositions were produced, 3.06 wt% Ti and 3.8 wt% Ti.

Isothermally aged specimens were heat treated for 48 hours at 725 °C. Multistep heat treatments were selected on the basis of a review of the literature that indicated low temperature steps early in the aging sequence would increase the driving force for nucleation of the hardening phase.^{8,9} Multistep aged specimens were heat treated for 4 hours at 725 °C, plus 5 hours at 650 °C, plus 44 hours at 725 °C. These heat treatments are similar to those used to produce bronze-processed Nb₃Sn superconductors.

Table 1. Composition of A-286 Stainless Steel

C	Mn	Si	Cr	Ni	Ti	Al	Mo	Fe
0.05	1.3	0.6	15.0	25.0	2.15	0.15	1.0	BAL

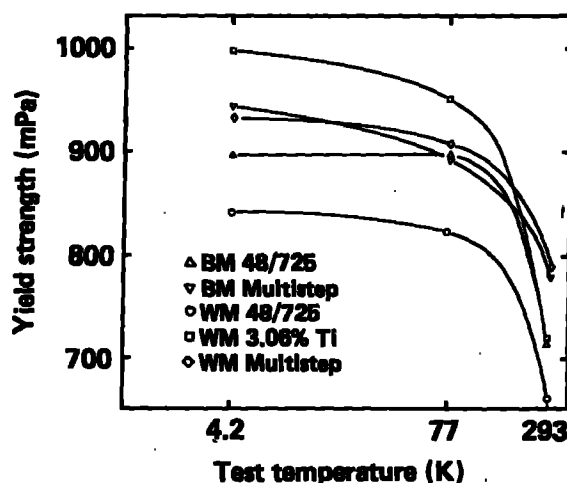


Figure 1. Yield strength vs temperature for well and base metal.

Tensile tests were performed using a machine equipped with a compression-tube load train and a liquid helium cryostat. Tests were conducted using a strain rate of 3.3×10^{-4} /s. Test specimens were flat tensiles with a 25.4-mm gauge length. Elongation during liquid helium tests was monitored using a clip gauge.

Aging response was determined using microhardness measurements. All values reported are the average of at least five indents. Weld indents were made at the weld centerline.

RESULTS

The yield strengths versus temperature for commercial-weld and base-metal, modified-chemistry and multistep heat-treated weld specimens are shown in Figure 1. The commercial-composition weld metal aged for 48 hours at 725 °C (WM 48/725) shows a lower yield strength throughout the temperature range than similarly heat-treated base plate. Multistep heat-treated weld metal shows a close matching of yield strength with isothermally aged base plate at room temperature and 77 K; however, the 4-K yield strength is higher. It should be noted that multistep aging influences the yield strength of both the weld and base plate. The multistep aged base-plate yield strength has increased to that of comparably aged weld metal. Increasing the weld Ti content to 3.06 wt% followed by isothermal aging at 725 °C increases the yield strength, particularly at low temperatures where it exceeds that of the base plate.

Failure in the isothermal and modified-chemistry-weld specimens is by ductile rupture at the center of the weld zone. Failure in the multistep aged weld occurred by intergranular fracture in the heat-affected zone (HAZ). The failure of the base metal specimens also occurred by intergranular fracture.

Figure 2 shows the isothermal aging response of the base metal, commercial-chemistry, and modified-chemistry (3.06 wt% Ti) welds heat treated at 725 °C. The commercial-chemistry weld shows a slower aging response and lower peak hardness than does the base metal. The addition of Ti to the weld pool increases the aging rate and gives a peak hardness that is similar to the base plate. The hardness peak occurs at times used for Nb₃Sn superconductor processing.

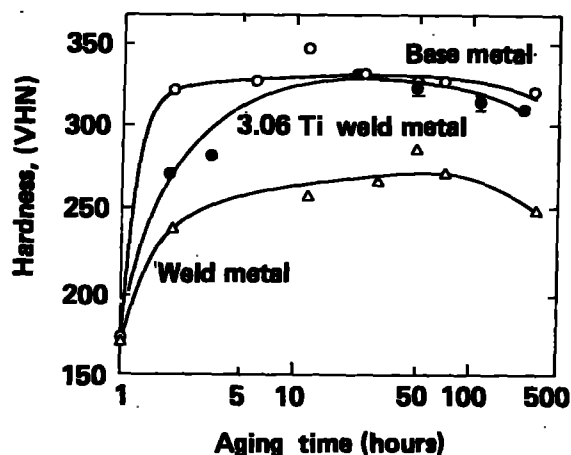


Figure 2. Isothermal aging response of base metal, commercial-, and modified-chemistry weld metal.

Figure 3 shows the aging response of isothermal, and multistep heat-treated weld and base metal. The inclusion of a low temperature step (5 hours/650 °C) raises the weld and base metal hardness slightly. Returning to 725 °C aging results in no significant change in the base metal hardness. The weld, however, shows a continuing hardening trend. The peak hardness is close to that of the base metal and occurs near 40 hours of aging.

Characterization of the weld microstructure shows the isothermally aged weld metal to have a precipitate-free-zone volume fraction of approximately 40% (Figure 4a). The 3.06% Ti weld is approximately 20% precipitate free (Figure 4b). The multistep aged welds show no evidence of distinct precipitate-free-zone formation (Figure 4c). However, TEM analysis shows considerable coarsening of the γ' hardening phase at the dendrite cores. Isothermally aged weld containing 3.80 wt% Ti shows no evidence of precipitate free zones, but rapid formation of the cellular η phase is seen (Figure 4d).

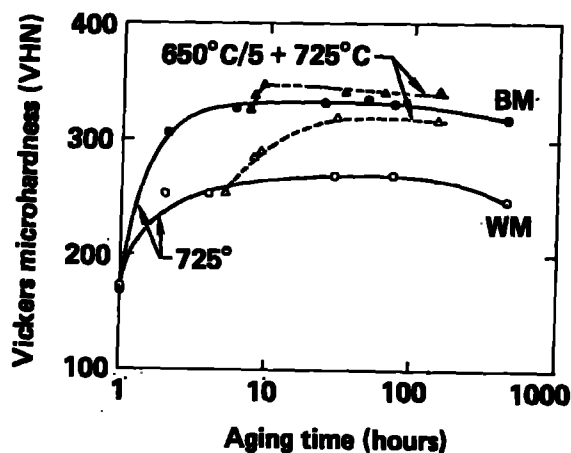


Figure 3. Aging response of multistep heat-treated weld and base metal.

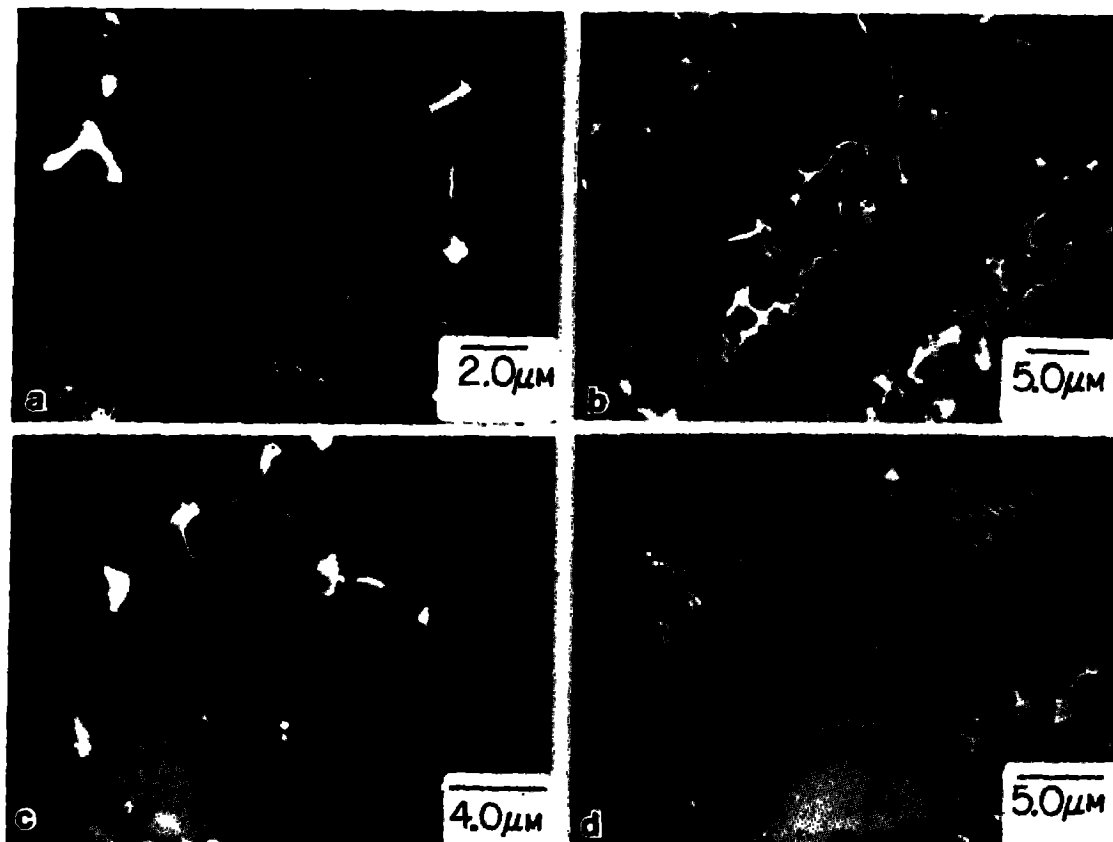


Figure 4. Weld microstructure: (a) commercial chemistry (48/725/°C), (b) 3.06% Ti (48/725/°C), (c) multistep aging, and (d) 3.81% Ti (48/725/°C).

DISCUSSION

The low yield strengths of commercial-chemistry, isothermally heat-treated welds of A-286 and JBK-75 are directly attributable to the formation of precipitate-free zones. As shown previously, the precipitate-free zones result from the segregation of Ti during weld pool solidification.^{6,7} As determined by STEM microanalysis, the minimum Ti concentration for the precipitation of the hardening phase during 725 °C aging is approximately 1.8 wt%.

Additions of Ti to the weld pool cause the critical Ti content to be reached at an earlier stage of solidification, reducing the extent of precipitate-free-zone formation. High local volume fractions of γ' are seen in the outer regions of the dendrites and contribute to strengthening.⁶ Formation of the precipitate-free zones in the modified-chemistry welds was observed to occur at Ti contents of 1.8 wt%.

The formation of the η phase in the weld containing 3.8 wt% Ti is not unexpected. High levels of Ti have long been known to cause early overaging in Fe-base superalloys.^{10,11} Therefore, Ti levels should be maintained well below this level. Ti levels of 3.06 wt% have not been observed to result in the extensive formation of η phase. Close control of the weld Ti content at levels below 3.06 wt% should result in matching yield strengths for the weld and base metal at 4 K.

The work of Irvine et al.⁸ indicates that the precipitation of γ' is also temperature dependent. Hughes⁹ has shown that, at 800 °C, 25-Ni 15-Cr superalloys should precipitate the γ' phase at Ti concentrations as low as 1.0 wt%. Therefore, in A-286 and JBK-75 welds, precipitation should not be limited by Ti solubility in the matrix.

The observed response of A-286 to multistep heat treatments can be explained if γ' growth is nucleation limited. The low temperature step (650 °C) results in a slight increase in strength in the weld and base metal. The weld dendrite cores nucleate γ' in the Ti-lean regions due to a high effective supercooling. The base metal hardening presumably results from secondary nucleation due to suppression of the solubility limit.

Increasing the temperature to 725 °C has no effect on the base metal, i.e., the solubility limit has been shifted up. The weld, however, continues to harden. This is due to the growth of stable nuclei formed during the low temperature step. Nucleation at the center of the dendrite cores is difficult, as reflected by the rapid coarsening of the γ' .¹²

The use of a multistep heat treatment produces a weld microstructure that does not have distinct precipitate-free zones and a strength that is near that of similarly heat-treated base plate. The addition of low temperature steps in the aging sequence has been shown to be beneficial in some bronze-processed superconductors.^{13,14}

The intergranular failure observed in the base plate regardless of aging conditions results from the high solution temperatures employed.^{15,16} These high temperatures were required to yield large grain sizes in the base plate so as to eliminate Hall-Petch effects when comparing base-metal and coarse-grained-weld microstructures.

CONCLUSIONS

Isothermal aging at temperatures of 725 °C and higher results in the formation of precipitate-free zones in A-286 weldments. The precipitate-free zones persist at long aging times and are responsible for the lower yield strength of the weld as compared to similarly aged base metal.

Small additions of Ti to the weld reduce the extent of the precipitate-free zones and increase the low temperature yield strength. Weld Ti contents of 3.06 wt% raise the strength above that of the base plate at 4 K without significant formation of η phase at long aging times. Ti levels of 3.80 wt% result in the formation of η phase at short aging times.

Precipitation of the hardening phase in A-286 is nucleation limited in the Ti-lean dendrite cores. Multistep heat treatments are effective in promoting nucleation of the hardening phase at the dendrite cores, and increase the weld yield strength. Matching yield strengths at 4 K are achievable between weld and base metal using multistep heat treatments. JBK-75, due to its similar chemistry, is expected to behave similarly to heat treatment and chemistry modification.

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